Field Results From Three Campaigns To Validate The Performance Of The Miniaturized Laser Heterodyne Radiometer (Mini-LHR) For Measuring Carbon Dioxide And Methane In The Atmospheric Column

J. Houston Miller[1]; Greg B. Clarke[2], Hilary Melroy[1]; Lesley Ott[3]; Emily L. Wilson[2]

[1]GWU, Department of Chemistry; [2]NASA GSFC, Laser Remote Sensing Lab, Code 694

[3] NASA GSFC Global Modeling and Assimilation Office, Code 610.1

Abstract

In a collaboration between NASA GSFC and GWU, a low-cost, surface instrument is being developed that can continuously monitor key carbon cycle gases in the atmospheric column: carbon dioxide (CO_2) and methane (CH_4). The instrument is based on a miniaturized, laser heterodyne radiometer (LHR) using near infrared (NIR) telecom lasers. Despite relatively weak absorption line strengths in this spectral region, spectrally-resolved atmospheric column absorptions for these two molecules fall in the range of 60-80% and thus sensitive and precise measurements of column concentrations are possible.

In the last year, the instrument was deployed for field measurements at Park Falls, Wisconsin; Castle Airport near Atwater, California; and at the NOAA Mauna Loa Observatory in Hawaii. For each subsequent campaign, improvement in the figures of merit for the instrument has been observed. In the latest work the absorbance noise is approaching 0.002 optical density (OD) noise on a 1.8 OD signal.

An overview of the measurement campaigns and the data retrieval algorithm for the calculation of column concentrations will be presented. For light transmission through the atmosphere, it is necessary to account for variation of pressure, temperature, composition, and refractive index through the atmosphere that are all functions of latitude, longitude, time of day, altitude, etc. For temperature, pressure, and humidity profiles with altitude we use the Modern-Era Retrospective Analysis for Research and Applications (MERRA) data. Spectral simulation is accomplished by integrating short-path segments along the trajectory using the SpecSyn spectral simulation suite developed at GW. Column concentrations are extracted by minimizing residuals between observed and modeled spectrum using the Nelder-Mead simplex algorithm.

We will also present an assessment of uncertainty in the reported concentrations from assumptions made in the meteorological data, LHR instrument and tracker noise, and radio frequency bandwidth and describe additional future goals in instrument development and deployment targets.

Figure 1: Map illustrating AERONET's 450+ monitoring stations worldwide (shown by red squares) . Figure credit: NASA Goddard

Background

Laser heterodyne radiometry (LHR) is a technique for detecting weak signals that was adapted from radio receiver technology. In a radio receiver, a weak input signal from a radio antenna is mixed with a stronger local oscillator signal. The mixed signal (beat frequency) has a frequency equal to the difference between the input signal and the local oscillator. The intermediate frequency is amplified and sent to a detector that extracts the audio from the signal. In a laser heterodyne radiometer, the weak input signal is light that has undergone absorption by a trace gas. The local oscillator is a laser at a near-by frequency - in this case a low-cost distributed feedback (DFB) telecommunications laser. These two light waves are superimposed in either a beamsplitter or in a fiber coupler (as is the case in this design). The signals are mixed in the detector, and the RF beat frequency is extracted. Changes in the column concentration of the trace gas are realized through analyzing changes in the beat frequency amplitude. By bandpass filtering the RF and tuning the laser through an absorption feature, trace gas concentrations can be found as a function of altitude.

Figure 2: An autonomous AERONET instrument is shown (left). LHR instrument with optical components labeled (right). The LHR instrument will piggy-back to the AERONET instrument in a simple and non-invasive fashion. By coupling these two instruments, concentrations of greenhouse gases as a function of altitude can be determined. Photo credit: NASA Goddard
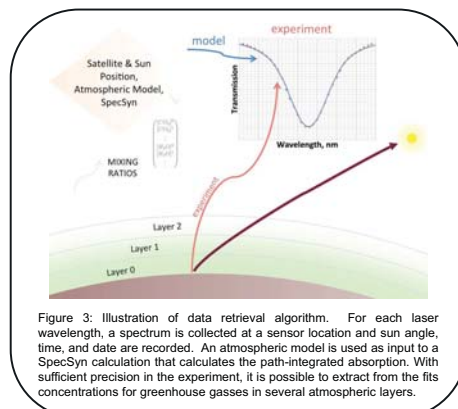

Figure 3: Illustration of data retrieval algorithm. For each laser wavelength, a spectrum is collected at a sensor location and sun angle, time, and date are recorded. An atmospheric model is used as input to a SpecSyn calculation that calculates the path-integrated absorption. With sufficient precision in the experiment, it is possible to extract from the fits concentrations for greenhouse gasses in several atmospheric layers.

Simulating Spectra

Atmospheric spectra are simulated for the column using the *SpecSyn* spectral simulation package developed at The George Washington University (GWU). This software uses physical parameters from the HITRAN Spectral database (2008 edition) to model CO_2 spectra. The integrated path absorption spectrum is calculated using the initial sun angle and pressure and temperature profiles taken from Modern-Era Retrospective Analysis for Research and Applications (MERRA). Instrument broadening is then added to the simulated spectrum, with an initial assumption of 3 GHz (0.025 nm). The experimental spectrum is then fit to the instrument-broadened simulated spectrum using a Nelder-Mead simplex algorithm. Figure 3 shows data for a typical synthetic spectrum (blue line) and measured spectrum (red symbols).
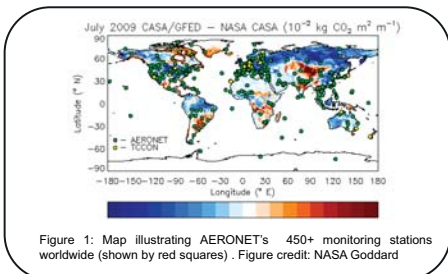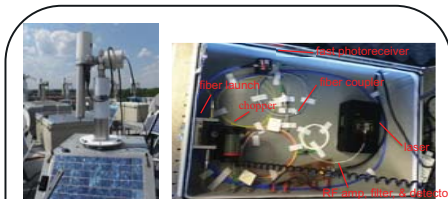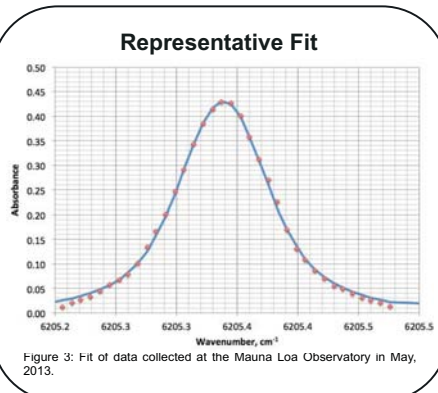
Representative Fit

Figure 3: Fit of data collected at the Mauna Loa Observatory in May, 2013.
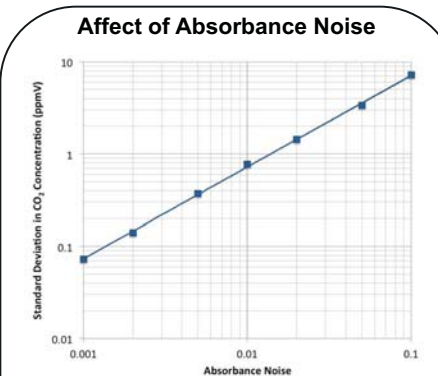
Affect of Absorbance Noise

Figure 4: To estimate the uncertainty in this fitting algorithm, absorbance noise was added to a simulated spectra and the resulting "experimental" spectrum was fit. This process was repeated for 100 trials at several absorbance nose levels. The results of these Monte Carlo trials, shown above, indicate that a noise level of 0.01 OD leads to an uncertainty of just under 1 ppmV in CO_2 column mixing ratio,

2012-2013 Field Campaigns

While development of the miniaturized LHR began in 2009, beyond ongoing testing at Goddard Space Flight Center, regular measurements in the atmospheric column did not begin until September 2012. The instrument has been field tested at the TCCON site in Park Falls, WI where it was compared with their Fourier Transform Spectrometer (September 2012), at Castle Airport in Atwater, CA during the ASCENDS DC-8 field campaign (February 2013), and at NOAA's Mauna Loa Observatory, HI where it operated in April and May of 2013.

Over the development and field-testing period, the mini-LHR has undergone significant improvements to reduce error. The absorbance noise for a single scan has decreased from ~0.021 to ~0.009 to ~0.006 for field campaigns in Park Falls, Castle Airport, Mauna Loa, respectively. Precision can be further improved by averaging consecutive scans. Figure 5 shows the number of averaged scans required to reach an absorbance noise for each field test. During the first field campaign at Park Falls, the scan time was ~20 minutes and the lowest absorbance noise reached was 0.02 for an average of three scans (~1 hour of data). At the second field campaign in Atwater, the scan time was reduced to about 2 1⁄2 minutes by transitioning from LabView to Python data acquisition software, resulting in a absorbance noise of about 0.003 for 45 minutes of averaged data. During the third field campaign at Mauna Loa Observatory, the scan time was further reduced to less than a minute and an absorbance noise of 0.0024 was reached in about 6 scans (~6 minutes of data). Once again referring to Figure 4 an estimated precision of ~0.2 ppmv is determined.
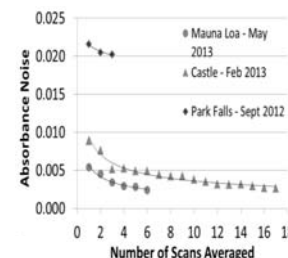
Future Plans

New opportunities for mini-LHR deployment are currently being explored including:
- A multi-disciplinary, multi-scaled study to measure methane (CH_4) and carbon dioxide (CO_2) above thawing permafrost at three sites near near Fairbanks, AK.
- A regional network of sensors in the Washington DC area to help validate higher resolution grid simulations of GEOS-5 data.
- CubeSat deployment of a mini-LHR system for Limb measurements of CO_2 in arctic regions.

Acknowledgements